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Impact of Atmospheric Aerosols on Climate of the West Coast of India with Special Reference to Mangaluru Region

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Impact of Atmospheric Aerosols on Climate of the West Coast of India with Special Reference to Mangaluru Region

Introduction

Atmospheric aerosols are tiny particles or droplets suspended in the Earth's atmosphere. They can be solid or liquid and vary greatly in size, composition, and origin (Seinfeld et al., 1998). The natural sources of atmospheric aerosols are volcanic eruptions, sea spray, dust storms, biogenic, and the anthropogenic sources are combustion of fossil fuels, industrial processes, biomass burning, urban activities (Andreae et al.,2009; Petzold & Kärcher,2012; Nikkath and Selvi, 2024). Aerosols play a crucial role in the Earth's climate system. They can scatter and absorb sunlight, affecting the Earth's radiation balance. Additionally, aerosols serve as nuclei for cloud formation, influencing cloud properties and precipitation patterns (Pippal et al., 2024b; Farid et al., 2022; Persad et al., 2022).

In regions like the west coast of India, aerosols can significantly influence monsoon patterns. By altering the temperature gradient between the land and the ocean, aerosols can affect the timing, intensity, and distribution of monsoon rains (Singh et al., 2018). Aerosols can also contribute to extreme weather events by modifying atmospheric stability and circulation patterns. For instance, they can enhance or suppress the development of storms and cyclones (Wang et al., 2022; Akinyoola et al., 2024).

The west coast of India, including major cities like Mumbai, Mangaluru, and Kochi, is densely populated. High population density leads to increased emissions from vehicles, residential heating, and cooking, contributing significantly to aerosol concentrations. The west coast is home to numerous industries, including refineries, chemical plants, and manufacturing units. These industries emit a variety of aerosols, including sulfates, nitrates, and black carbon. Industrial activities are vital

for the region's economy. However, they also contribute to air pollution. Studying aerosols helps in balancing economic growth with environmental sustainability (Mehta & Khushboo, 2022; Persad et al., 2022).

Some aerosols, like black carbon (soot) and certain organic aerosols, absorb solar radiation. This absorption heats the aerosol particles and the surrounding air, leading to a warming effect in the atmosphere (Myhre et al., 2013). The overall impact of aerosols on climate depends on the balance between scattering and absorbing aerosols. While scattering aerosols tend to cool the climate, absorbing aerosols can offset this cooling by warming the atmosphere. The net effect is complex and varies regionally based on the types and concentrations of aerosols present (Chen et al., 2023).

Aerosols act as cloud condensation nuclei (CCN), around which water vapor condenses to form cloud droplets. An increase in aerosol concentration leads to more CCN, resulting in a higher number of smaller cloud droplets. This process is known as the Twomey effect or first indirect effect. Smaller cloud droplets increase the cloud's reflectivity, or albedo, because they scatter sunlight more effectively than larger droplets. This enhanced reflectivity leads to more sunlight being reflected back into space, contributing to a cooling effect on the Earth's surface. This phenomenon is also referred to as the cloud albedo effect. Smaller droplets are less likely to coalesce into larger droplets that can fall as precipitation. This can delay the onset of rainfall, leading to longer-lived clouds. This effect is known as the second indirect effect or cloud lifetime effect (Nabat et al., 2022).

The alteration in cloud properties can influence regional precipitation patterns. For instance, increased aerosol concentrations can lead to reduced rainfall in some areas while enhancing it in others, depending on the local meteorological conditions (Fan et al ., 2012). The changes in cloud properties due to aerosols can have both cooling and warming effects on the climate. While increased cloud albedo generally leads to

cooling, the extended cloud lifetime can also trap more longwave radiation, potentially leading to localized warming (Chen et al., 2024; Liu et al., 2014).

The west coast of India has experienced more erratic monsoon patterns in recent years. Studies indicate that the southwest monsoon, which brings the majority of the region's rainfall, is becoming increasingly unpredictable. This variability can lead to periods of both excessive rainfall and drought (Prabhu, 2024; Kumar & Manjunatha, 2021b). Research shows a trend towards more convective rainfall, characterized by intense, short-duration rain events. This shift is linked to the warming of the Arabian Sea, which enhances the moisture content and instability of the atmosphere (Sreenath et al., 2022). The west coast has seen a significant increase in surface temperatures. This warming is partly due to the absorption of solar radiation by black carbon aerosols, which heats the atmosphere and the surface (Sreenath et al., 2022).

The warming of the Arabian Sea has led to more frequent and intense cyclones. These storms bring heavy rainfall, strong winds, and storm surges, causing widespread damage (Ratnakaran & Abish, 2023; Soltanpour et al., 2021). The combination of intense rainfall and rising sea levels has increased the risk of flooding along the west coast. Coastal cities are particularly vulnerable to storm surges and high tides, which can inundate low-lying areas (Sreenath et al., 2022). Aerosols can influence monsoon patterns by altering the temperature gradient between land and ocean. This can lead to changes in the timing, intensity, and distribution of monsoon rains, particularly in regions like South Asia (Singh et al., 2018b; Wu et al., 2015). Studies have shown that aerosols can increase the likelihood of extreme weather events, such as heavy rainfall and storms. This is due to their impact on atmospheric stability and cloud dynamics (Persad et al., 2022). Aerosols can affect ecosystems by altering nutrient cycles and reducing visibility. For example, dust aerosols can transport nutrients across continents, impacting soil and water quality (Kok et al., 2023)

Studies have shown significant trends in aerosol concentrations over the Arabian Sea and the Bay of Bengal. Research using satellite data and field measurements has highlighted the variability in aerosol optical properties and their vertical distribution (Liu et al., 2021). These studies indicate that the west coast of India is a major aerosol hotspot, influenced by both natural and anthropogenic sources (Vinoj et al., 2014; Solanki et al., 2023). Research has documented the vertical extent of aerosols, particularly dust, which can reach up to 6 km in the atmosphere over western India (Mehta et al., 2022). This vertical distribution is crucial for understanding the transport and impact of aerosols on regional climate (Kala et al., 2022).

Aerosols have been found to influence the Indian monsoon by altering the temperature gradient between the land and the ocean. This can lead to changes in the timing, intensity, and distribution of monsoon rains (Kumar et al., 2024). For example, increased aerosol concentrations have been linked to delayed monsoon onset and reduced rainfall in some regions. Studies have shown that aerosols can modify cloud properties, leading to changes in precipitation patterns. Increased aerosol concentrations can result in more frequent but less intense rainfall events (Kumar & Manjunatha, 2021b). There is a paucity of long-term observational data on aerosol concentrations and properties over the west coast of India. More continuous monitoring and field campaigns are needed to fill this gap (Jin et al., 2023; Kala et al., 2022; Varghese et al., 2021. The interactions between aerosols, clouds, and precipitation are complex and not fully understood. Further research is needed to unravel these interactions and their implications for regional climate.

Area of Investigation

Mangaluru is located on the west coast of India, as shown in Fig. 1, abutting the Western Ghats mountain range in the east, consisting of dense forest, and the Arabian Sea on the west, with rapidly growing industries and urban development. The city is located around 350 km (219 miles) west of Bangalore and is connected by four kinds of transportation: air, road, rail, and sea. According to Pesaresi et al.

(2015), the urban agglomeration has a population of 725,033, with a population density of 2616/km^2. Rolling hills, rivers, and laterite soil characterize the city's scenery. Mangaluru is one of the 100 smart cities to be constructed in India, located 22 meters above mean sea level. Mangaluru has experienced rapid industrialization and urbanization in recent years, significantly increasing atmospheric aerosol concentrations. This region, owing to the generation of anthropogenic aerosols and the transport of sea salt from the adjacent Arabian Sea, is also impacted by the long-range transport of mineral dust from the African and Middle Eastern deserts (Sijikumar et al., 2015; Jin et al., 2021). Mangaluru is influenced by the southwest monsoon and has a tropical climate dominated by four seasons: winter, spring, summer, and fall.

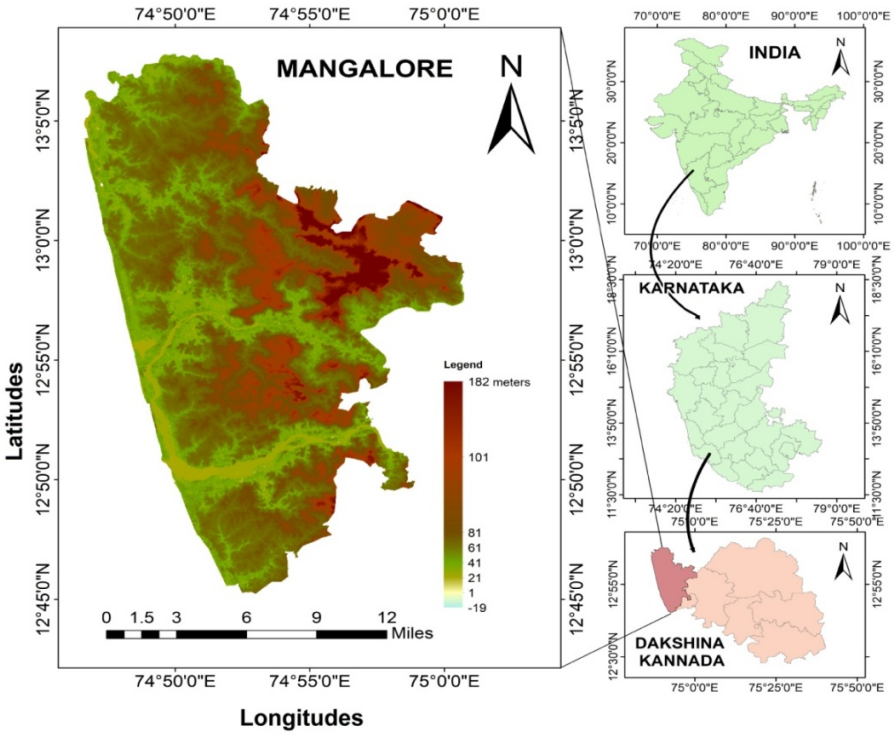

Fig. 1.1: Topographical elevation map of Mangaluru, Karnataka, India.

Objectives

The objectives of this study are to

- Know state atmospheric pollution along the west coast of India and its potential impacts on climate, rainfall, hydrological cycle, agriculture, visibility, and human health.
- Determine the origin/sources and characterization of atmospheric aerosols/dust at fortnightly intervals, particularly in a sub-urban region near Mangalore, and their seasonal and inter-annual variations with respect to the monsoon cycle.
- Assess the impact of regional/global atmospheric processes and climate cycles on the atmospheric processes along the west coast of India.

Outiline of the Thesis

The thesis will be prepared tentatively under the following chapters.

Chapter 1: Introduction

This chapter comprises a general introduction, a literature review, and background information with scope and objectives. Here, an overview of the present understanding of the thesis work is discussed. The thesis primarily bases its literature review on reference work from a variety of sources, such as research articles, conference proceedings, books, and authoritative reports. This comprehensive review aims to synthesize existing knowledge on atmospheric aerosols, their sources, and their impacts on India's west coast climate. By critically analyzing these references, the review identifies key trends, gaps, and areas for further research, thereby providing a solid foundation for the subsequent chapters of the thesis.

Chapter 2: Materials and Methods

This chapter outlines the detailed explanation of sampling techniques, data acquisition methods, data processing, analytical techniques, and tools used in this

research. The methodology is structured to ensure a comprehensive understanding of the research process and to provide a clear roadmap for replicating the study. In this chapter, the primary and secondary data sources will be briefly explained, along with GIS and statistical software utilized.

The primary goal of this research is to understand the impact of atmospheric aerosols on India's west coast climate. By analyzing the composition and distribution of aerosols, we aim to identify their sources, transport mechanisms, and effects on regional climate patterns.

The rainwater collection stations were set up at two different locations to compare the spatial variability in aerosol deposition and analyze the differences in chemical composition between urban and rural environments. One rainwater collection was established at the Mangalore University campus and the other in Karwar, in a pristine region. Rainwater samples were collected for three years, i.e., during the period 2019-2021. A large (15-inch) polypropylene funnel (with a bird guard and tygone tubing to prevent bird dropping contamination of samples and reduce evaporation water from the sampler) was utilized to set up a station. The rainwater samples were stored by adding preservatives such as thymol and $HgCl_2$ to prevent microbial growth and chemical changes. Important nutrients, such as phosphates, silicates, nitrates, and nitrites, in samples were evaluated using spectrophotometry in accordance with normal water and wastewater analytical protocols. By analyzing the nutrient concentrations in rainwater and river water, researchers can gain valuable insights into the nutrient flux within the hydrological cycle. The samples were also analyzed for total organic carbon (TOC) and total nitrogen (TN) concentrations using a Schimadzu TOC analyzer. The analysis provides insights into the carbon and nitrogen content of the rainwater, which are key indicators of pollution levels. The results were then compared across the two locations to identify any significant differences in nutrient deposition. This data was crucial for understanding the sources and impacts of atmospheric aerosols on local ecosystems.

Satellite data is crucial in aerosol research because it provides comprehensive, high-resolution observations over large geographic areas, allowing researchers to monitor aerosols over vast and remote areas, including oceans and deserts, which are otherwise difficult to access. Satellites equipped with multi-spectral sensors such as MODIS (Moderate Resolution Imaging Spectroradiometer), MISR (Multi-angle Imaging Spectro Radiometer), and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) were broadly utilized to differentiate between various types of aerosols (e.g., dust, smoke, sea salt) and to study the aerosol impact on the microphysical properties of clouds.

The satellite sensors provide valuable data for understanding aerosols' distribution, composition, and impact on climate and air quality (Lee et al., 2009). Accessing satellite data typically involves using various online databases and platforms that provide direct downloads, such as NASA Earthdata, CALIPSO Data, and GIOVANNI. Further, the data has been processed by removing noise and correcting errors. Software such as ArcGIS and QGIS were used to analyze satellite-derived data.

Chapter 3: Identification of the Potential Sources of Aerosols over the monsoon-dominated, Southern West Coast of India

In this chapter, we investigate the intricate dynamics of aerosol sources and their distribution over the southern west coast of India, with special reference to the Mangaluru region. Our study spans from 2005 to 2020, focusing on analyzing the seasonal distribution of Aerosol Optical Depth (AOD) and classifying the aerosol species into absorbing and non-absorbing categories (Prasad et al., 2004). By identifying the monthly sources of aerosols, we aim to understand the variability and impact of these particles on regional air quality and climate. Moreover, we examine the influence of wind speed on aerosol distribution, providing insights into the transport mechanisms of these particles (Bhowmik et al., 2024). The seasonal distribution of absorbing aerosols is scrutinized to identify the dominant absorbing aerosol species and their sources (Asutosh & Vinoj, 2024). To enhance our analysis, we utilize LIDAR Level 1 aerosol profile products in conjunction with NOAA's HYSPLIT

model, offering a comprehensive perspective on aerosol vertical profiles and their potential trajectories (NOAA HYSPLIT Model). The findings from this chapter, with a focus on the Mangaluru region, will contribute significantly to the body of knowledge on aerosol behavior in monsoon-affected regions, with implications for environmental management and policy-making.

Chapter 4: Influence of Hygroscopic Aerosols for Understanding the Cloud Microphysical Properties in the Atmosphere over Mangaluru

Atmospheric aerosols play a critical role as precursors in influencing cloud microphysical properties and rainfall patterns. This study aims to elucidate the importance of aerosols on cloud properties within the summer monsoon-dominated region of Mangaluru, located on the southwest coast of India. The comprehensive analysis includes various datasets and methodologies to provide a deeper understanding of these interactions. Aerosol optical depth (AOD) and Angstrom exponent (AE) datasets, along with meteorological data, are employed to examine the spatial and temporal distributions of aerosols. These parameters are essential in understanding the concentration and types of aerosols present in the atmosphere. Studies have shown that AOD and AE can significantly impact cloud formation and precipitation processes (Kaufman et al., 2002; Remer et al., 2005). Additionally, the air mass back trajectories were computed using the hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) model. This model helps trace the origins and pathways of air masses transporting aerosols to the study region. Understanding these trajectories is vital for identifying the sources of aerosols and their transport mechanisms. Previous research has demonstrated the effectiveness of HYSPLIT in tracking air mass movements and understanding their impact on regional aerosol concentrations (Stein et al., 2015). Furthermore, the study explores the influence of hygroscopic aerosols on cloud microphysical properties. Hygroscopic aerosols can act as cloud condensation nuclei (CCN), promoting cloud droplet formation and altering cloud microphysical characteristics (Andreae & Rosenfeld, 2008). The impact of these aerosols on cloud properties and rainfall in the Mangaluru region is examined

through detailed analysis of observational and model data. This research contributes to a broader understanding of how aerosols affect cloud microphysical properties such as cloud top pressure (CTP), cloud top temperature (CTT), cloud fraction (CF), water vapor (WV), and precipitation in monsoon-dominated regions, with significant implications for regional climate and weather prediction.

Chapter 5: Influence of atmospheric parameters on rainfall patterns in western India

This study investigates the impact of aerosols on cloud properties in the monsoon-dominated region of Mangaluru, located on India's southwest coast. The research highlights how El Niño and La Niña events influence rainfall, with El Niño typically leading to drought conditions and La Niña resulting in increased rainfall. Key atmospheric parameters, such as Aerosol Optical Depth (AOD), dust mass concentration, black carbon (BC) mass concentration, and PM2.5 mass concentration, are analyzed for their variability and impact on air quality and visibility. These parameters help in understanding the concentration, types, and sources of aerosols, and their influence on atmospheric conditions.

Regression analysis was used to identify significant trends in these atmospheric parameters over the study period, providing insights into their relationships with precipitation. Principal Component Analysis (PCA), performed using SPSS software, was employed to identify the main factors affecting rainfall. PCA helps reduce the dimensionality of large datasets while retaining most of the data's variability, making it easier to understand the underlying structure. The findings contribute to a broader understanding of how atmospheric factors, influenced by El Niño and La Niña events, affect cloud formation, precipitation, and overall climate dynamics in the region. This knowledge is crucial for making more accurate predictions about rainfall patterns, which have significant implications for agriculture, water resources, and climate in the area.

Chapter 6 Physicochemical and nutrient analysis of rainwater

This study highlights the critical importance of analyzing rainwater quality. Rainwater serves as a vital source of fresh water, particularly in regions facing water scarcity. Monitoring rainwater quality helps identify contaminants, such as heavy metals, pathogens, and chemical pollutants, which can pose risks to human health and the environment. Understanding the physico-chemical properties of rainwater, such as pH, conductivity, and turbidity, is essential for assessing its suitability for various uses, including drinking, irrigation, and industrial processes. Regular water quality monitoring aids in developing effective pollution prevention and management strategies, ensuring compliance with environmental regulations and protecting aquatic ecosystems. By analyzing rainwater quality, researchers contribute to sustainable water management practices and mitigate the impacts of pollution on water resources.

This study also focuses on the physico-chemical properties and nutrients in rainwater. Parameters like pH, conductivity, turbidity, and temperature, along with nutrient concentrations such as nitrates, phosphates, ammonium, nitrites, and silicates, are crucial for understanding rainwater quality and its potential environmental impacts. These measurements provide insights into the effects of agricultural runoff, industrial emissions, and atmospheric deposition on water quality. Regular monitoring and analysis of these parameters support the development of effective water quality management strategies, helping to protect water resources and maintain ecological balance. By characterizing rainwater quality, researchers can promote sustainable water management practices and ensure the protection of both the environment and public health.

Chapter 7: Summary and conclusions

Atmospheric aerosols, which include dust, soot, sea salt, and other particles, play a significant role in the climate system by interacting with solar radiation and clouds. The west coast of India, particularly the Mangalore region, experiences a variety of aerosol sources, including natural sea salt from the ocean and anthropogenic emissions from industrial activities. The impact of atmospheric aerosols on India's west coast climate, with a focus on the Mangalore region, is multifaceted. Aerosols influence radiative forcing, cloud properties, and monsoon dynamics, which in turn affect regional climate patterns. Understanding these impacts is crucial for developing effective climate adaptation and mitigation strategies. Future research should focus on improving the accuracy of aerosol measurements and modeling to better predict their climatic effects and inform policy decisions.

This is followed by
References,
Publications and
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List of Publications

1. Manjunatha, B.R., Balakrishna, K., Jose, J., Ahmed, A., Rajesha, R., Naveen Kumar, A. (2022). *Importance* of the Geochemistry of Nearshore Sediments in the Realm of Heavy Metal Pollution Assessment. In: Armstrong-Altrin, J.S., Pandarinath, K., Verma, S.K. (eds) Geochemical Treasures and Petrogenetic Processes. Springer, Singapore. https://doi.org/10.1007/978-981-19-4782-7_4

2. Srivastava, J., Manoj, M. C., Manjunatha, B. R., Yoganandan, V., Jose, J., Balakrishna, K., et al. (2022). Delineation of terrestrial and marine productivity in the southwestern continental margin of India. Journal of Asian Earth Sciences, 230, 105203. https://doi.org/10.1016/j.jseaes.2022.105203

Publications under review

1. Identification of the Potential Sources of Aerosols over an Urban Region of the monsoon-dominated, Southern West Coast of India. (Journal of Indian Society of Remote Sensing)

2. Influence of Hygroscopic Aerosols for Understanding the Cloud Microphysical Properties in the Atmosphere over Mangaluru, Southwest Coast of India. (Journal of Indian Society of Remote Sensing)

Conference Presentations

1. Recent advancements in Marine Geology and Geoinformatics- 2023: “Spatio temporal properties of cloud properties over Mangalore.” Organized by “Department of Marine Geology, Mangalore University, Mangalalore-India.”

2. 42nd IIG Annual Meet- 2021: “Seasonal Distribution and Identification of Potential Sources of Aerosols over an Urban City, Central West Coast of India. Organized by “Department of Geography, Savitribai Phule Pune University (SPPU), in association with Institute of Indian Geographers (IIG).”

3. ITHES- 2021: “A glimpse of the Tropical River Water Quality, Central West Coast of India”. Organized by “Water & Environment Division, Department of Civil Engineering, NIT Warangal.”

4. SWARDAM- 2021: “A Pilot Study on Water Quality of Dakshina Kannada District, Karnataka, West Coast of India”. Organized by “Department of Civil Engineering, Government College of Engineering, Aurangabad, Maharashtra, India.”

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